Interactions of Waves, Tidal Currents and Riverine Outflow and their Effects on Sediment Transport (RIVET II)

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LONG-TERM GOALS

Developing a robust coastal modeling system to study the dynamics of tidally-pulsed river plume and the resulting trapping, storage and resuspension of sediments in a wave-dominated environment. The model can be further used to interpret water column and seabed dynamics using the observed surface features through remote-sensing.

OBJECTIVES

- Studying how waves and their evolution over complex bathymetry and current patterns affect the hydrodynamics and turbulent mixing in the plume nearfield.
- Studying trapping, storage and resuspension of various classes of sediment (clay, silt, aggregates and sand) due to the tidally-pulsed Columbia River plume nearfield.
- Enhancement of an existing non-hydrostatic coastal model NHWAVE with a wave-current interaction module for strong shear flow appropriate for river outflow and adaptive mesh capability in order to carry out system-scale simulation with high resolution in the plume nearfield.

SIGNIFICANCE

Studying the mixing of riverine freshwater and coastal water is the fundamental step to further understand the balance of a coastal/estuarine ecosystem (e.g., Hickey et al. 2010), seabed properties, sediment budgets (Gelfenbaum & Kaminsky 2010), and the sustainable management of the fluvial-estuary habitat (e.g., damming, dredging). The nearfield of a river plume represents an energetic environment because it involves the lift-off and subsequent lateral spreading of the freshwater outflow. As the lateral spreading must cause flow acceleration, the plume near field is highly turbulent (Hetland 2005; MacDonald et al. 2007) and may be dominated by locally generated shear instabilities (Geyer et al. 2010). With improved sensor and computing technology, recent field and numerical studies provided significant insights into the complex hydrodynamics near the plume lift-off zone and nearfield (e.g., MacDonald et al. 2007; Kilcher & Nash 2010; Elias et al. 2012). However, researchers are only beginning to understand how the near field plume dynamics affect the delivery of sediments. For instance, high level of suspended sediment concentration is often observed in the plume nearfield (Spahn et al.

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2009; Nowacki et al. 2012; W. R. Geyer, WHOI, personal communication). However, the dominant mechanisms responsible for such elevated level of sediment concentration are unclear (e.g., local resuspension, or deposition of sediments from the upstream, or both). Moreover, it is widely acknowledged that the river mouth is where surface waves encounter strong tidal currents and/or river outflows. However, the role of waves on the plume near field, especially in terms of turbulent mixing and bottom shear stress, remains to be investigated.

In this study, we carry out process-based numerical investigation focusing on the "critical interfaces", namely the plume nearfield, which connects the estuary, inner shelf and adjacent beaches. A non-hydrostatic coastal modeling system NHWAVE (Ma et al. 2012) is adopted to investigate wave-current interaction, turbulent mixing and sediment resuspension in tidally-pulsed Columbia River plume nearfield.

APPROACH

We utilize the model NHWAVE, which was recently developed by Ma et al (2012) to study the propagation of fully dispersive, fully nonlinear surface waves in complex 3D coastal environments. NHWAVE is formulated in time-dependent, surface and terrain-following σ - coordinates. The model is wave-resolving and provides instantaneous descriptions of surface displacement and wave orbital velocities. Wave breaking is handled naturally by the shock-capturing properties of the model's finite volume TVD formulation. The model is similar in intent to other non-hydrostatic solvers such as SWASH (Zijlema et al, 2011), and has been found to be of comparable or better accuracy than most similar models, particularly in terms of the number of vertical levels needed in application. The model is fully parallelized using MPI. Due to large domain that needs to be covered in the Columbia River nearfield, NHWAVE is used here as a wave-averaged non-hydrostatic coastal model. The resulting system would require the inclusion of wave forcing terms in NHWAVE as well as the modification of a wave model such as SWAN to incorporate new expressions for wave action density and flux which are consistent with the recently developed generalized theory (Dong & Kirby 2012). The application of a non-hydrostatic model in a large domain can incur excessive computational cost due to the need to solve the resulting pressure Poisson equation over the full extent of the domain. The present structure of NHWAVE approaches this problem by partitioning pressure into hydrostatic and non-hydrostatic components, thus limiting the application of the Poisson solver to the nonhydrostatic correction. In our wave-averaged NHWAVE, we propose to establish a more efficient computational framework by limiting the nonhydrostatic computation to regions where deviations from hydrostatic are likely to be important, i.e., evolving frontal structures, regions of strong vertical shear and resulting instability and mixing, and regions of active sediment erosion/resuspension. Adaptive mesh capability is implemented in NHWAVE to achieve highly refined mesh in these regions to capture the non-hydrostatic effects.

WORK COMPLETED

To cover a wide range of processes in the Columbia River estuary, mouth and continental shelf, an adaptive mesh refinement (AMR) is incorporated into NHWAVE. The AMR version of NHWAVE is developed based on the quad-tree algorithm described in Berger et al. (2011). The NHWAVE model is treated as an independent module and links to an AMR interface with a hierarchical indexing structure. The modulized AMR configuration makes it easy to develop additional model components inside the NHWAVE module without making any change in the AMR structure. Refinement procedure uses physically meaningful constraints to ask for refinement when local quantities, such as salinity gradient, kinetic energy, etc., are higher than a prescribed value. The parallelization of AMR followed the existing MPI algorithm in NHWAVE with equal CPU load for each subgrid level. The AMR version of NHWAVE is being tested in several idealized 3D domains on the Linux cluster mills.hpc.udel.edu at the University of Delaware. In the context of this study, we have been working on a 2D-vertical domain selected along Columbia River channel. Preliminary results will be shown in the following section.

The development of a wave-averaged version of NHWAVE is being carried out under the present ONR funding and a newly funded NSF project. In particular, Dong and Kirby (2012, 2013) have developed a wave-averaged model formulation which generalizes the vortex force formulation of McWilliams et al (2004) and Ardhuin et al (2008) to the case of currents with arbitrarily strong vertical shear, for application to wave-current interaction problems in strongly-stratified estuaries and river mouths. The resulting extension to the NHWAVE model framework then consists of wave-forcing terms added to the NHWAVE equations. Following the model coupling framework of NearCoM-TVD (Chen et al, 2013), the wave-averaged NHWAVE is being coupled to SWAN wave model (Booij et al, 1999), and we use the more general spectral version of the theory corresponding to Ardhuin et al (2008). The SWAN model is modified with corresponding to arbitrary shear in the extended wave equations.

RESULTS

To model multi-scale interactions of river plume, tidal current and sharply changing bathymetry at the mouth of Columbia River (MCR), the newly developed AMR version of NHWAVE is used to investigate the small scale feature of highly stratified flow, turbulence structure and associated sediment transport processes. The AMR allows us to zoom in on the moving fronts of riverine fresh water, salt wedge or other interested local phenomena without a need to over-resolve the entire computational domain. As an initial test, we developed a 2D-vertical model which extends from 70 meters water depth to 20 km upstream along the river channel using measured bathymetry data in 10-meter resolution. The model input is idealized with M2 tidal boundary conditions at both offshore and upstream boundaries, and fresh water condition at the upstream boundary. The case uses 10-meter resolution for the finest subgrid and 200-meter resolution for the root grid.

Figure 1 demonstrates a preliminary result from the test case with a fixed subgrid. The upper panel shows a snapshot of salinity distribution and velocity field at the beginning of flood tide, which are obtained from the root grid. The left bottom panel is a zoom-in view from the second level subgrid domain. It is shown that, at the beginning of flood tide, the salt wedge is driven by the strongly stratified flow near the sea bottom. A votex is generated by the baroclinic and nonhydrostatic forcing at the front of the salt wedge where both horizontal and vertical motions are significantly large as shown in the right bottom panel. The high near bed velocity and strong turbulent mixing (not shown here) are expected to have significant effects on local sediment resuspension. In addition, the subgrid is able to resolve the small scale bathymetric feature and thus provides more details of flow-sea bed interaction. We are working on more effective criteria for subgrid refinment with both salinity gradient and turbulent kenetic energy taken into account. We will work on extend the AMR model into a more realistic 3D domain of MCR and incorporate the new measureemnt data into the study.

As a test for the wave-averaged NHWAVE model, we run a case corresponding to Tejada-Martinez and Grosch (2007) with a constant Stokes drift. Figure 2 shows plots of velocity components on transects taken perpendicular to the co-linear wind and wave direction. The top panel shows the perturbation to the wind-driven mean flow in the wind direction, while the middle pannels show the total transverse and vertical velocity components. The velocities of the Langmuir circulation are comparable in magnitude to those predicted by Tejada-Martinez and Grosch (2007). The further development of coupled NHWAVE-SWAN model will continue in the project.

IMPACT/APPLICATIONS

Lead by Dr. Kirby, we are also supported by a NSF project (OCE-1334325; Collaborative Research: The interaction of waves, tidal currents and river outflows and their effects on the delivery and resuspension of sediments in the near field; collaborate with Dr. Gangfang Ma of ODU) to study broader issues of wave-current interaction and sediment delivery in the nearfield of tidally-pulsed river plumes. The ongoing ONR project provides valuable field data and scientific input of Columbia River system that are important to the successs of the NSF project.

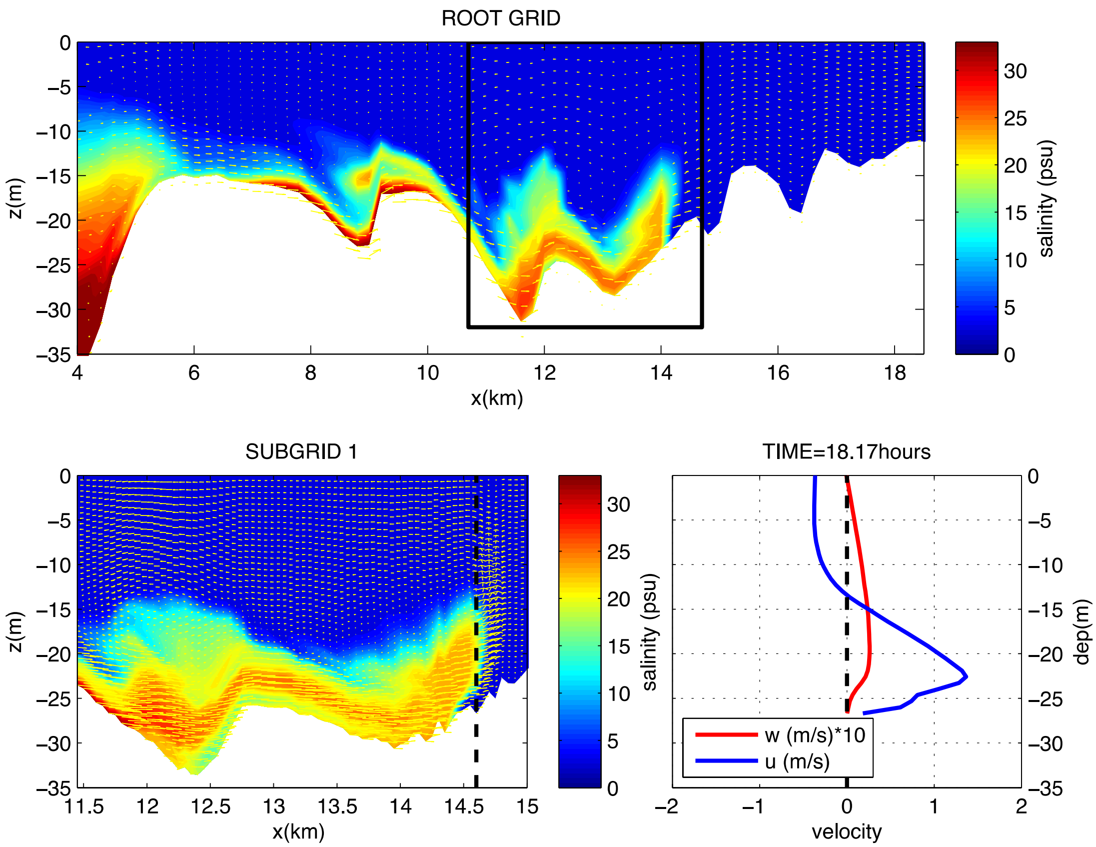

Figure 1. Snapshot of salinity distribution of velocity field at the beginning of flood tide at MCR. Upper panel: root grid result, black rectangle represents the zoom-in area in the second level subgrid; Left bottom: subgrid result; Right bottom: velocity profiles at the vertical section shown in black dashed line in the left bottom panel.

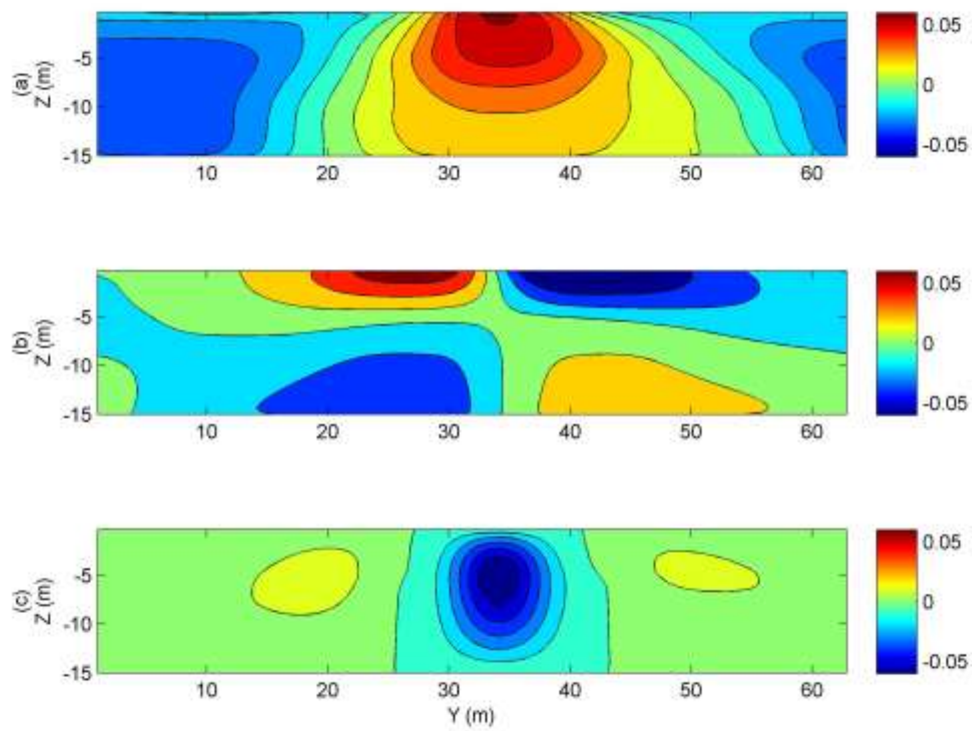

Figure 2: Transverse structure of Langmuir cell predicted by wave-averaged NHWAVE using a k-epsilon closure. Top: x-direction perturbation to laterally averaged wind-driven, wave-modified flow. Middle: y-direction flow. Bottom: Vertical flow. Unit is in m/s.

REFERENCES

Berger, M J, D L George, R J LeVeque, K T Mandli, 2011. The GeoClaw software for depth-averaged flows with adaptive refinement. Advances in Water Resources, 34, 11951206.

Dong, Z. and Kirby, J. T., 2012, Theoretical and numerical study of wave-current interaction in strongly sheared flows, Proc. 33d Int. Conf. Coastal Engrng., Santander.

Dong, Z. and Kirby, J. T., 2013, Wave-current interaction in strongly sheared mean flows: Theory, in preparation for J. Fluid Mech.

Elias E., Gelfenbaum, G., van de Westhuysen, A. (2012) Validation of a coupled wave-flow model in high energy setting: the mouth of the Columbia River, J. Geophys. Res., in review.

Gelfenbaum, G., Kaminsky, G. M., (2010) Large-scale coastal change in the Columbia river littoral cell: An overview, Marine Geology, 273, 1-10.

Geyer, W. R., Lavery, A. C., Scully, M. E. and Trowbridge, J. H., 2010, "Mixing by shear instability at high Reynolds number", *Geophys. Res. Lett.*, 37, L22607, doi:10.1029/2010GL045272.

Hetland, R. D., 2005, "Relating river plume structure to vertical mixing", *J. Phys. Oceanogr.*, 35, 1667-1688.

Hickey, B. M., et al. (2010), River Influences on Shelf Ecosystems: Introduction and synthesis, J. Geophys. Res., 115, C00B17, doi:10.1029/2009JC005452.

Kilcher, L. F., and J. D. Nash (2010), Structure and dynamics of the Columbia River tidal plume front, J. Geophys. Res., 115, C05S90, doi:10.1029/2009JC006066.

MacDonald, D. G., Goodman, L. and R. D. Hetland, R. D., 2007, "Turbulent dissipation in a near-field river plume: A comparison of control volume and microstructure observations with a numerical model", *J. Geophys. Res.*, 112, C07026, doi:10.1029/2006JC004075.

Nowacki, D. J., Horner-Devine, A. R., Nash, J. D., and Jay, D. A., (2012) Rapid sediment removal from the Columbia River plume near field, Cont. Shelf Res., 35, 16-28.

Spahn, E. Y., A. R. Horner-Devine, J. D. Nash, and L. F. Kilcher (2009), Particle resuspension in the Columbia River plume near-field, J. Geophys. Res., 114, C00B14, doi:10.1029/2008JC004986.

Simenstad, C. A., Small, L. F., McIntire, C. D., Jay, D. A., Sherwood, C., (1990) Columbia River Estuary studies: An introduction to the estuary, a brief history, and prior studies, Progress in Oceanography 25, 1–13.

Tejada-Martnez, A. E. and Grosch, C. E., 2007, Langmuir turbulence in shallow water. Part 2. Large-eddy simulation, J. Fluid Mech., 576, 63-108.

Zijlema, M., Stelling, G. and Smit, P., 2011, "SWASH: An operational public domain code for simulating wave fields and rapidly varied flows in coastal waters", *Coastal Engrng.*, 58, 992-1012.

PUBLICATIONS

1. Shi, F., Ma, G., Kirby, J., & Hsu, T.-J. (2012). Applications of a TVD solver in a suite of coastal engineering model. *Coastal Engineering Proceedings, 1*(33), currents.31. doi:10.9753/icce.v33.currents.31 [PUBLISHED].
2. Shi, F., Ma, G., Kirby, J., and Hsu, T.-J. (2013). Adaptive mesh refinement of a non-hydrostatic model in a river plume application, 34th International Conference on Coastal Engineering [SUBMITTED]
3. Chen, J.-L., Shi, F., Hsu, T.-J., Kirby, J. T., (2013) NearCoM-TVD - a quasi-3D nearshore circulation and sediment transport model. [IN PREPARATION]